# A Re-Examination of the Origins of the Peculiar Velocity Field Within the Local Supercluster

David Burstein

*Arizona State University, Dept. of Physics and Astronomy, Box 871504, Tempe, AZ 85287-1504*

**Abstract.**
The recent re-evaulation of the peculiar velocity field outside the Local Supercluster (Dekel et al. 1999) has permitted a re-examination of the origins of the peculiar velocity field within the Local Supercluster using the Mark III Catalog of Galaxy Peculiar Velocities. It is shown that the large-scale coherent pattern of peculiar velocities within the LSC are well-fit by a combination of the Outside-Region-(generated)-Motions (O-R-M) from the Potent model with a Virgocentric infall pattern that produces 220 km s$^{-1}$ of Virgocentric infall at the Local Group towards the Virgo cluster moving at 88 km s$^{-1}$ towards the Local Group. The part of the LG CMB motion this model cannot fit is that perpendicular to the Supergalactic plane. On what size scale this SGZ motion of the Local Group is shared by neighboring galaxies cannot be determined from the present data set, but can be found if we can accurately measure galaxy distances close to the Galactic plane.

## 1. The Four Issues to be Addressed

In the Mark III Catalog (Willick et al. 1995, 1996) the distance of the Virgo cluster (VC) is $D_{VC} = 1330 \pm 52$ km s$^{-1}$. The heliocentric radial velocity of the VC ($V_{VC}$(helio)) from Huchra (1996) is 1094$\pm$35 km s$^{-1}$. Combine this with the heliocentric peculiar motion of the Sun in the Cosmic Microwave Background (CMB) frame of 368.6 km s$^{-1}$ towards l = 264.7°, b = 48.2°, yields a CMB radial velocity for the VC ($V_{VC}$(CMB)) of 1420 $\pm$ 35 km s$^{-1}$. If we combine $V_{VC}$(CMB) with the peculiar velocity of the Local Group (LG) in the CMB frame (372 km s$^{-1}$) in the direction of the VC, we find the LG and the VC move towards each other in the CMB reference frame with a mutual velocity of $V_{pec}(LG : VC) = 282 \pm 63$ km s$^{-1}$. Four issues can be addressed from these data:

1) How much of the CMB motion between the LG and the VC is generated by the VC itself (i.e., classic "Virgocentric infall" motion), how much is generated by masses on larger size scales?

2) The peculiar velocities of the galaxy groups defined to be within the Coma-Sculptor (C-S) Cloud by Tully (1987) can be demonstrably shown to share most of the LG CMB peculiar velocity (e.g. Faber & Burstein 1988; Tully

1988). Much of this motion ($\sim$ 300 km s$^{-1}$) is directed perpendicular to the Supergalactic plane. Why? How?

3) As viewed in the LG reference frame, galaxy groups within the C-S Cloud are moving towards each other. How much of these motions are generated by masses within the C-S Cloud and how much are externally generated?

4) In the direction towards the Ursa Major (Umaj) cluster (+X, +Y SG coordinates), all galaxies with D $\leq$ 1800 km s$^{-1}$ have peculiar velocities moving towards the LG. How much of these inward motions are generated by mass within the Local Supercluster (LSC), and how much by mass outside it?

Why rexamine these issues now? Based on the Mark III database and on a new POTENT methodology, Dekel et al. (1999) have generated a more accurate model of the peculiar motions generated *within* the LSC by masses *outside* the LSC. For the present paper, Ami Eldar and Avishai Dekel have kindly calculated from this model the "outside–region–(generated)–motions" (O-R-M) for galaxies within a distance of 3000 km s$^{-1}$ from the masses outside this region. For this analysis, we use only the spiral galaxies in the Mark III database. We use the CMB velocity reference frame only for galaxies outside the C-S Cloud. The LG velocity velocity reference frame is used for galaxies inside the C-S Cloud (using the Yahil, Tammann & Sandage (1977) vector for the heliocentric to LG transformation), as these galaxies demonstrably share the LG peculiar velocities.

## 2. Virgocentric Infall By the Numbers

The O-R-M peculiar velocity of the LG is, in the CMB frame, (-399.5, 139.3, -52.4) km s$^{-1}$ in (X,Y,Z) Supergalactic coordinates, or 426.3 km s$^{-1}$ towards L = 160.8°, B = -7.0° (Galactic l = 307.8°, b = 18.2°). While this is essentially the same direction as found by Lynden-Bell et al. (1988) in the original 7Samurai analysis, the overall O-R-M velocity field predicts a lower peculiar velocity for the LG in this direction, as well as a more complex velocity field outside and within the LSC than the Great Attractor model used there and by Faber & Burstein (1988).

In the O-R-M model, the VC has a net CMB motion relative to the LG of -178 km s$^{-1}$, resulting in a VC peculiar velocity *in the direction of* (i.e., not relative to) the LG of Vpec(VC : LG)$_{\mathrm{O-R-M}} = 90 - 178 = -88$ km s$^{-1}$. The O-R-M model also gives the LG a peculiar velocity towards the direction of the VC of 227 km s$^{-1}$. This leaves a net peculiar velocity of the LG *in the direction of* the VC of Vpec(LG : VC)$_{\mathrm{O-R-M}} = 372 - 227 = 145$ km s$^{-1}$.

Note that, if we insist on keeping the VC peculiar motion to be zero in the CMB/O-R-M frame of motion, the net motion *between* the LG and the VC is 145 km s$^{-1}$. However, if we take at face value the calculated peculiar motion of the VC relative to the CMB/O-R-M frame (-88 km s$^{-1}$), we get the net motion *between* the LG and the VC to be $145 - (-88) = 233 \pm 63$ km s$^{-1}$. In other words, if we remove the outside gravitational influences from the Virgocentric infall issue, the Local Group is moving towards the Virgo cluster at a speed of $233 \pm 63$ km s$^{-1}$, and the VC itself is moving 88 km s$^{-1}$ towards the LG.

To model the residual velocity field within the LSC relative to the O-R-M model we use a Virgocentric infall (Vinfall) model based on that used by Lynden-Bell et al. (a linearized model of that proposed by Schechter 1980). In

this model, we nominally assign a LG Virgocentric infall velocity of 220 km s$^{-1}$, leaving a residual of $-13 \pm 63$ km s$^{-1}$ of LG motion relative to the VC; i.e., well within the noise. Likewise, the combined O-R-M+Vinfall model leaves a net LG motion towards the center of Umaj of +15 km s$^{-1}$, with an error at least as large as that towards the VC. As one will see in the graphs at the end of the paper, the combined O-R-M + Vinfall model accounts for all but $\sim$ 100 km s$^{-1}$ systematic motions *within* the LSC, also within the known noise of galaxy peculiar motions.

## 3. The Local Anomaly by the Numbers

The CMB motion of the LG is 592 km s$^{-1}$ towards l = 276.0°, b = 23.6° (L = 146.0°, B = -33.9°). Subtracting the LG O-R-M motion, 426 km s$^{-1}$ towards l = 307.8°, b = 18.2° (L = 160.8°, B = -7.0°), we get a net motion of the LG relative to the O-R-M model of 309 km s$^{-1}$ towards l = 228.9°, b = 19.8° (L = 93.5°, B = -63.9°). Removing a Virgocentric infall of 220 km s$^{-1}$ towards l = 283.8°, b = 74.5° (L = 102.9°, B = -2.4°) yields a net motion of the LG relative to the combined O-R-M+Vinfall models of 273 km s$^{-1}$ towards l = 222.9°, b = -4.7° (L = 18.9°, B = -85.3°).

Because both the O-R-M vector and the Vinfall vectors lie so close to the Supergalactic plane (7° and 2.4°, respectively), the -330.1 km s$^{-1}$ Z-component of the LG CMB motion cannot be fit by either component. Thus, we are left with a component of the Local Group's CMB velocity that is larger than its Virgocentric infall velocity, in a direction almost exactly perpendicular to the Supergalactic plane - the Local Anomaly.

The problem with understanding this part of the Local Anomaly motion lies, of course, with the direction it is located within our Galaxy - within 5° of the Galactic plane. Given that the Supergalactic plane is nearly perpendicular to the Galactic plane, it comes as little suprise that almost all of the galaxies known within the LSC lie within the Supergalactic plane.

## 4. The Pictorial Representations of the Model Fits

Here we concentrate on presenting the residual motions within the LSC *after* this model is subtracted from the observed peculiar velocity field. The interested reader is referred to Burstein et al. (1996) for how the peculiar velocity field appears before this model-fit. As in Burstein et al., we restrict our picture of the peculiar of motions of LSC galaxies to those galaxies lying within ±22.5° of the Supergalactic plane, and within ±45° of the Supergalactic Y direction. The planar cut removes issues pertaining to galaxy infall relative to the Supergalactic plane; the Y-direction cut restricts our view to those motions that are primarily directed towards the two largest masses within the LSC — VC and Umaj.

Figure 1 shows the peculiar velocity field relative to the O-R-M+Vinfall model, as viewed from the direction of the north Supergalactic pole, with peculiar velocities of the galaxies plotted in their full (i.e., not *projected* velocities), a la′ Lynden-Bell et al. For this view alone, we include the peculiar velocities of the galaxies known to be in the VC.

Figure 2a shows the peculiar velocity field for the same galaxies as in Figure 1, relative to just the O-R-M model. Fig. 2a views the peculiar velocities

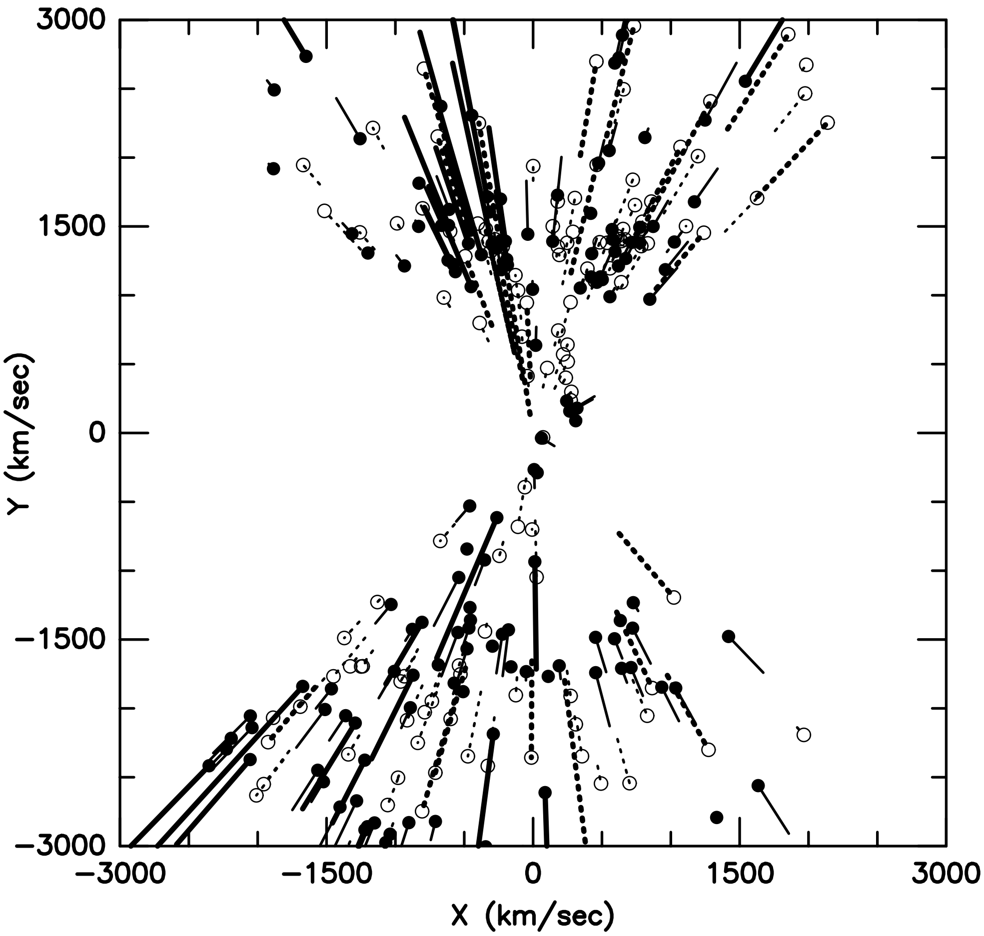


Figure 1. The peculiar velocity field of the Mark III catalog for those galaxies within $\pm 22.5^{\circ}$ of the Supergalactic plane, limited to $\pm 45^{\circ}$ of the SGY direction, relative to the combined Outer-Region-(generated)-Model plus Virgocentric infall model as discussed in the text. In this model, the Virgo cluster itself is given a velocity of 88 km $s^{-1}$ towards the Local Group.

along the Y-axis as if removed from the flow, negating the sign of peculiar velocities in the -Y direction. Comparison of this figure with Fig. 5a in Burstein et al. shows that the O-R-M model removes the apparent infall towards the LG for galaxies with Y $\leq -1000$ km s$^{-1}$. The O-R-M model now makes it clear that the apparent infall velocities seen along the Y axis are primarily a LSC phenomenon, rather than one of a larger region.

Figure 2b shows the peculiar velocity field along the Y axis relative to the combined O-R-M+Vinfall model velocity field (in this and subsequent views, galaxies are excluded if they lie within 5.7° of the VC direction, and within 530 km s$^{-1}$ of the VC distance). As stated earlier, it is apparent that the combination of the O-R-M + Vinfall velocity fields fit well the velocity field within the LSC, modulo residual motions of $\sim 100$ km s$^{-1}$ remaining, as evident by the coherent residual motions of the galaxies within the Coma-Sculptor Cloud.

Figures 3a–d show the views in a 35° cone towards the VC (left-hand side) and in a 25° cone towards Umaj (RHS). The top graphs are the peculiar velocities of galaxies as seen in the observed CMB + Local Anomaly reference frame. The bottom graphs are the peculiar velocities of the galaxies in these directions relative to the combined O-R-M+Vinfall model. It is clear the combined model not only removes all evidence of infall on the near side of the VC, it also removes essentially all of the inwards motions of galaxies in the the UMaj direction. There is even a suggestion in Fig. 3d of a slight infall pattern relative to Umaj itself.

## 5. Conclusion

The well-known quadrupole peculiar velocity field within the LSC is well-fit by a a combination of two physically-generated motions: a) Those generated by mass distributed around the Local Supercluster at $D \geq 3000$ km s$^{-1}$ (from the O-R-M model); and b) the Virgocentric infall (Vinfall) pattern from a Virgo Cluster moving at 88 km $^{-1}$ motion towards the LG, which produces 220 km s$^{-1}$ of infall of the LG towards the VC. (If we insist the VC have no peculiar motion in the O-R-M model, there would be an LG infall velocity to the VC in the O-R-M model of 132 km s$^{-1}$.) The strong observed infall motion of the Ursa Major region is well-fit by the combined O-R-M+Vinfall model *plus* the net infall motion of the Virgo cluster towards the LG. If one insists on putting the Virgo cluster at rest relative to the model, all the galaxies in the Ursa Major region are then given an overall 88 km s$^{-1}$ peculiar motion towards the LG.

Two kinds of coherent motions remain relative to the combined model: a) $\sim 100$ km s$^{-1}$ motions, coherent over 1000-1500 km s$^{-1}$ size scales (e.g., what we see for the C-S Cloud). b) The Local Anomaly, now seen as a 270 km s$^{-1}$ motion of the Local Group nearly perpendicular to the Supergalactic plane. Is this SGZ motion just that of the Local Group, does it involve the whole Coma-Sculptor Cloud, or does it involved the whole LSC?

While the "Local Void" (cf. Tonry & Dressler, this meeting) is likely a contributant to the Local Anomaly motion, for it to "push" the LG stronger than the VC "pulls" us seems unlikely. As the bulk of our knowledge of LSC motions lie within the Supergalactic plane, it is improbable for us to know the full origin of the Local Anomaly without knowing the distances of galaxies behind the Zone of Avoidance of the Galactic plane. Saito et al. (1991) and

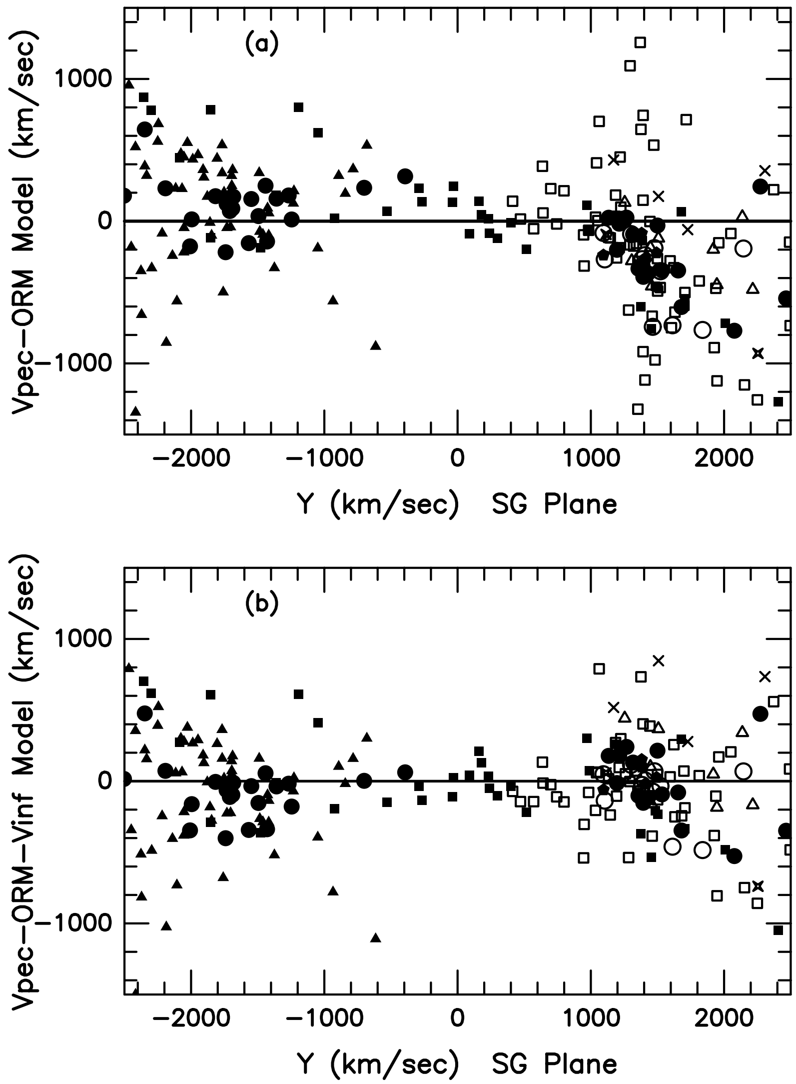


Figure 2. (a) The Mark III predicted peculiar velocities relative to the Outer-Region-(geneated)-Motion model, plotted versus SG ±Y direction for the galaxies shown in Figure 1. The sign of peculiar velocity is negated for -Y positions. Open symbols are galaxies within 35° of the Virgo cluster direction (l = 283°.8, b = 74°.5); closed symbols are galaxies in other directions. Circles denote galaxies with 2 or more separate observations; squares denote Aaronson et al. data; triangles Mathewson data; x's are data from Courteau and pentagons data from Willick; see Willick et al. 1995, 1996 for details. Comparing this figure to the analogous one in Burstein et al. 1996, one sees that the O-R-M model removes the infall pattern for galaxies with Y $< -1000$ km s$^{-1}$ as seen in the CMB reference frame. (b) The same galaxies as in (a), now with both the O-R-M and Virgocentric infall model subtracted. It is evident that the combination of the two models has removed all large-scale flows from within the Local Supercluster.

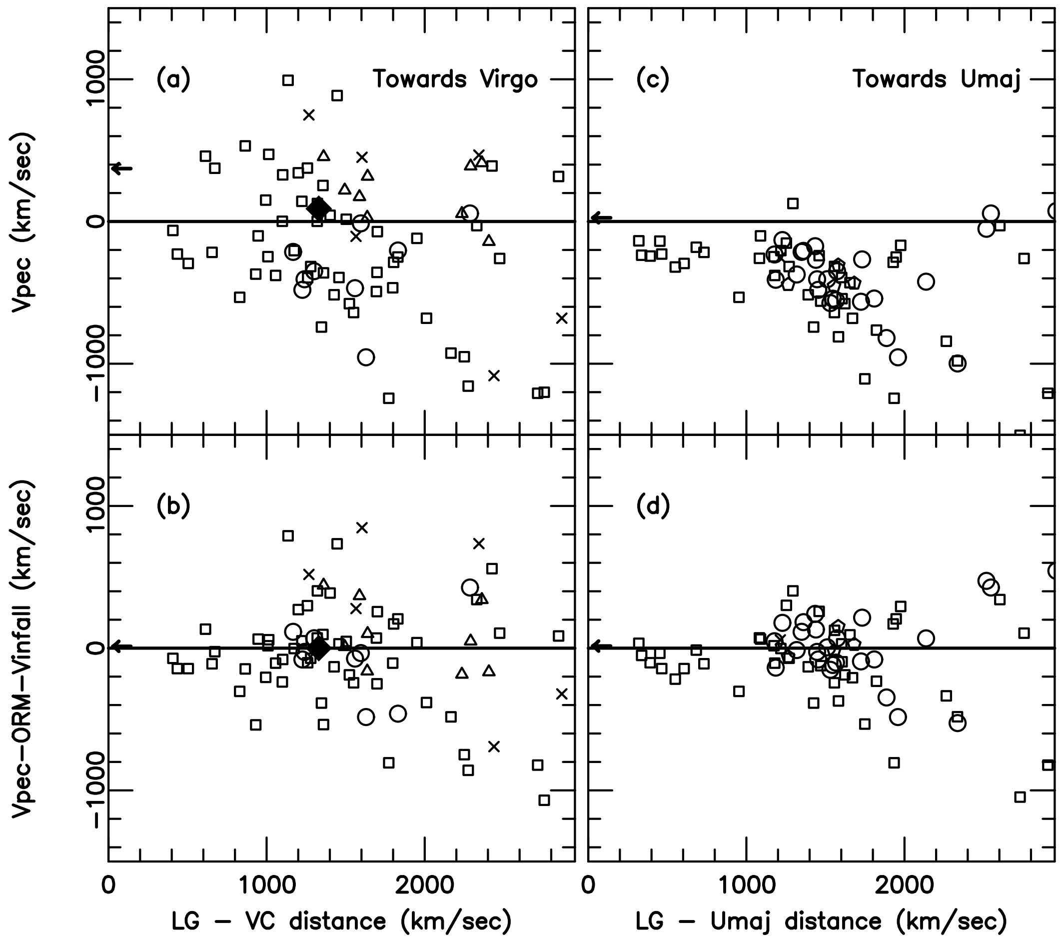


Figure 3. Left hand side (a,b): The peculiar motions of galaxies from Figure 1 that are also within a 35° cone centered on the direction of the VC ($l = 283.8°, b = 74.5°$), with VC galaxies excluded. Right hand side (c,d): The peculiar motions of galaxies from Figure 1 that are also within a 25° cone centered on the direction of Umaj (($l = 140°, b = 62°$). Top row (a,c): the observed CMB + Local Anomaly reference frame. Bottom row (b,d): relative to the combined O-R-M + Vinfall model. The large infall motion of the galaxies towards UMaj are removed by the model, as well as infall motions towards the VC. There is a hint of an infall pattern remaining relative to UMaj. Symbols the same as in Fig. 2; the arrows give the peculiar velocity of the Local Group in these directions in these reference frames.

Lahav et al. (1993) have shown that near l = 230°, b = -4° is a galaxy cluster in Puppis, heavily extincted by the Galaxy and masked by foreground stars. Given this cluster appears strongly in IRAS-detected galaxies, it is likely that it also contains a substantial number of early-type galaxies. If we can measure the distances to galaxies in the Puppis region, we can test whether the SGZ motion of the LG is shared by the whole LSC or not. If it is just the LG/C-S Cloud doing this motion, then we should simply see the reflex motion of the SGZ reflected in the peculiar velocities of the Puppis galaxies. If, on the other hand, the LSC and the Puppis Supercluster are being gravitationally drawn together, the galaxies in Puppis will show peculiar velocities towards us in substantial excess of the CMB reflex. This is a test definitely worth doing, albeit the known difficulties involved.

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